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# X-33 Flight Visualization

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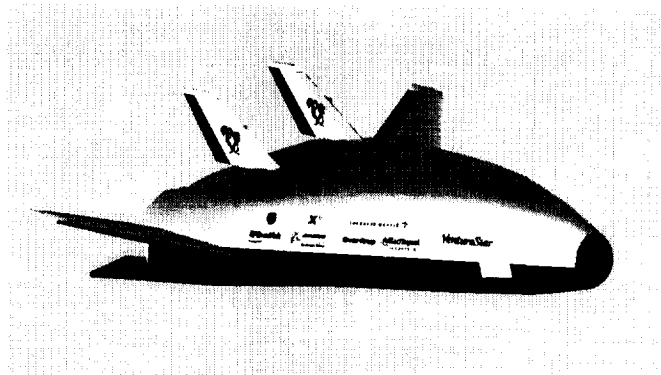
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*In early 1998, the NASA Space Transportation Programs Office and NASA Public Affairs jointly funded an activity under the Space Transportation Integrity Program (STIP) contract with Science Applications International Corporation (SAIC) to develop X-33 flight visualizations. This technical and management support effort was contracted by the X-33 Program Office of the NASA Marshall Space Flight Center's X-33 Program Office. This paper presents the technical approach and methodology used in developing pre-flight visualizations, as well as the plans and approach for real-time flight coverage visualizations of the X-33 reusable launch vehicle.*

## BACKGROUND

Science Applications International Corporation (SAIC) is supporting the NASA Marshall Space Flight Center (MSFC), NASA Public Affairs, and the Office of Aeronautics and Space Transportation Technology at NASA Headquarters. Within a broad-based work statement, the Space Technologies Operation of SAIC's Applied Technology Group provides technology and concepts assessment, management integration, and integrated design and engineering. A special and important component of this work relates to development of flight visualizations in support of the X-33 launch vehicle program being managed by the MSFC's Space Transportation Programs Office in Huntsville, Alabama. SAIC's work is being performed under MSFC Space Transportation Integrity Program contract NAS8-40197.

The X-33 is an approximately half-scale predecessor to America's first single-stage-to-orbit (SSTO) space transportation system (**Figure 1**). It is being built under a Cooperative Agreement between NASA and its industry partner, Lockheed-Martin, at the Lockheed-Martin Skunk Works in Palmdale, California. The X-33 program will demonstrate the key design features and ground/flight operational approaches to the SSTO concept, thus reducing the business and technical risks to the private sector in subsequent development of the full-scale Reusable Launch Vehicle (RLV) system. The goal of the privately financed RLV is to reduce launch transportation costs to low earth orbit by an order of magnitude.



**FIGURE 1.** X-33 Launch Vehicle

The first test flight of the X-33, in the summer of 1999, will be an unmanned, sub-orbital flight from its specially built launch site at Haystack Butte, near Edwards Air Force Base and NASA's Dryden Flight Research Center in California, to a landing strip four hundred and fifty miles away at the Michael Army Airfield Dugway Proving Ground in Utah. Plans include subsequent flights from Haystack Butte to a landing site at Malmstrom AFB in Montana. (Figure 2)

## FLIGHT VISUALIZATION OBJECTIVES

The objective of the first visualization task is to provide integrated visualizations of the X-33 flights via digital high-resolution videos, programmatic films, and web-site formats for public and programmatic information and outreach. The objective of the second visualization task is to provide a capability for coverage of the actual X-33 test flights. The first task was based on planned flight trajectory data. The second, or "Flight Coverage" task, will be accomplished via Near Real Time (NRT) visualizations for TV coverage of the flight based on the down-linked data stream from the X-33 vehicle as it flies from its launch site near Haystack Butte to its designated landing site(s) several hundred miles down range. Real-time view-position control of the flight paths will be determined by the NASA TV director. It is planned that the output data will be presented to NASA for integration into television broadcast coverage accessible to the public.

## A TEAM EFFORT

A team approach is being used by SAIC in developing X-33 flight visualizations in support of the NASA X-33 Program Office and NASA Public Affairs. It involves use of high-resolution terrain data provided by the NASA/Jet Propulsion Laboratory (JPL), digital renditions of the vehicle and ground operations by John Frassanito & Associates, software developed by Analytical Graphics, Inc., web-based presentation by Virtual Creations, Inc., together with close technical and operational coordination with the Lockheed-Martin Skunk Works (LMSW) and the NASA Dryden Flight Research Center (DFRC). The technical methodology involves integration of ground/flight video scenes, very high resolution terrain data and photographs with dynamic video representations of the checkout, launch, overland flight trajectory, approach and landing, and ground operations for the planned X-33 test flights. Figure 3 illustrates the participants' roles and their interrelationships within the Flight Visualization activity.

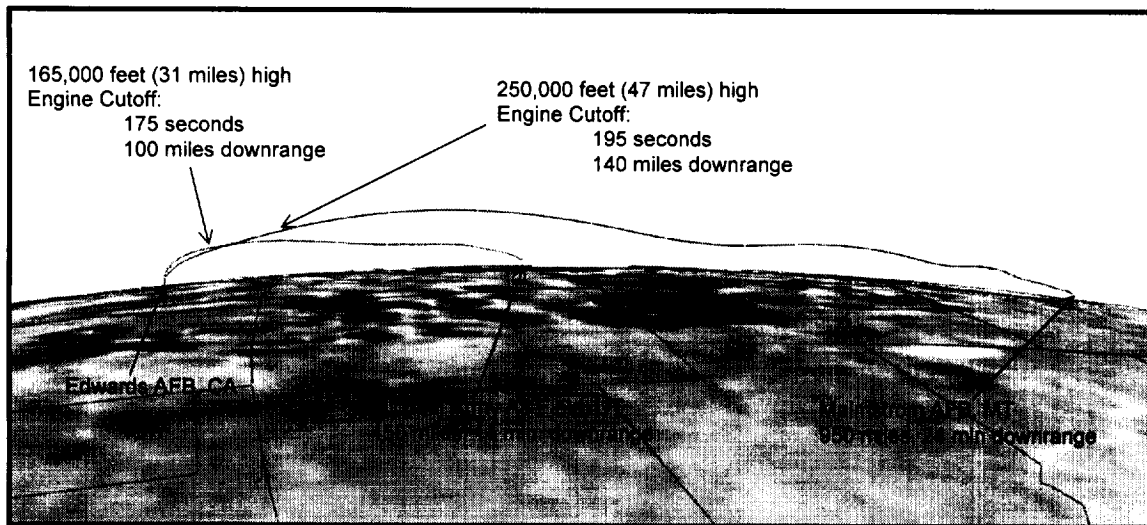
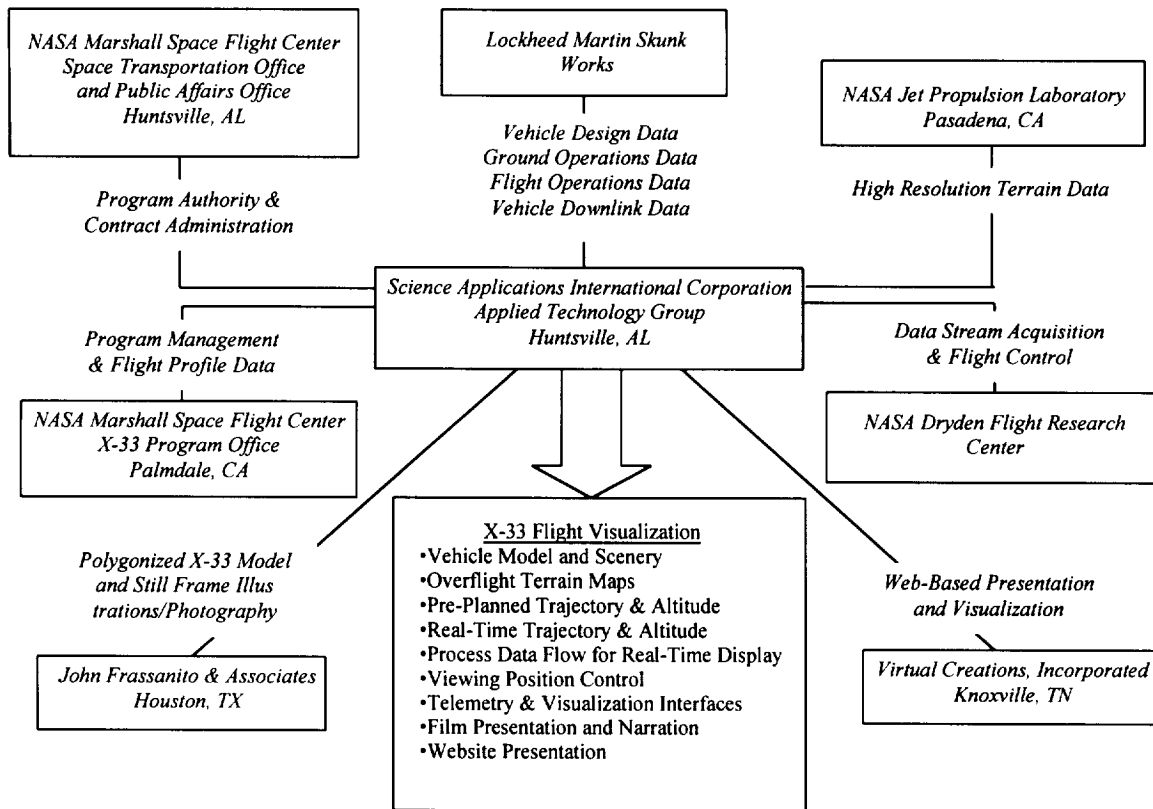


FIGURE 2. X-33 Flight Profiles



**FIGURE 3.** The X-33 Flight Visualization Activity

## THE VISUALIZATION PROCESS

The initial flight visualizations for SAIC's "Public and Programmatic Information and Outreach" task are based on flight profile data provided to SAIC by NASA. Later, during the actual flights, the vehicle data stream information will be acquired by NASA/Dryden as an integral part of the flight control activity. This data stream will also be simultaneously available to SAIC participants at Dryden for input to the "X-33 Flight Coverage" visualization. Virtual Creations Incorporated has supported SAIC in both of these tasks by preparing the visualizations for public web-site presentation. The availability and use of the real time visualizations and web-site data is determined and controlled by NASA Public Affairs prior to, and during, the X-33 flights.

SAIC creates scenarios of the planned X-33 flights using a software package developed by Analytical Graphics, Incorporated (AGI), called Satellite Tool Kit, Visualization Option (STK/VO). The videos combine the X-33 vehicle images, launch/landing scenes, overflight terrain images, and trajectory/attitude data.

### Vehicle Model and Scenery Data

SAIC uses a polygonized model of the X-33 vehicle derived from one developed by John Frassanito & Associates (JF&A) of Houston, Texas. JF&A also provides enhanced imagery of pre-flight launch and landing site scenes. The latter consist of lifelike digital visualizations depicting key preparation, launch, landing, and turnaround operations. The visualizations were generated using ray-tracing techniques, and feature combinations of highly detailed vehicle models, aerial photographs, and actual ground support personnel. The ray-tracing rendering of the scenes can consume many hours, but produce visualizations with realistic glints, shadows, and diffuse reflections. In contrast, the STK/VO model may be run and manipulated in real time. Due to current limitations in computer hardware, the terrain and vehicle model are not quite photorealistic, but are more than adequate.

## **Overflight Terrain Maps**

To depict terrain regions at sufficient fidelity for a visualization of high-altitude flight, SAIC chooses appropriate geographic bounds that are likely to be viewed by a virtual observer during flight. The geographic information consists of two parts...digital elevation data and terrain coloration ("textures").

An on-going project at JPL involves adapting a Landsat database for the entire western United States. JPL produces images in which seams are removed from overlapping image boundaries, along with a balancing of color and lighting differences that resulted from satellite imagery at different times. Although the Landsat images were collected in two infrared and one visible band, the JPL process is followed by a re-colorization by SAIC to provide earthlike tones. The background terrain is at a resolution of at least 30 meters, in full color, and is compressed to a digital size compatible with the existing STK/VO formats by AGI.

The texture files from JPL are in a portable pixel map format. They range in resolutions of 2048x2048 to 4096x4096. The physical size ranges from approximately 12 megabytes to approximately 49 megabytes, each covering geographical areas ranging from 0.5 degrees square to 10 degrees square. Digital Terrain Elevation Data (DTED), obtained from the National Imagery and Mapping Agency (NIMA), are used by SAIC for providing terrain elevations in the third simulation.

The STK/VO software has several features that aided in this work. One was the capability of assembling the geographic texture and elevation information into a single "globe" file. Since the total file sizes listed above were so large, it was impossible to depict the high-resolution images of the entire region of interest at once. The "globe" files facilitated the rapid switching of the data needed for a convincing simulation. Also, the software has an ability to record a smooth virtual view (or chase plane) path. Every time a flight is simulated, the exact same viewer position history may be shown. The repeatability of this view path makes it possible to develop a visualization in a piecemeal manner.

STK/VO has an option to output still frames from the VO window. When exercised, a still frame is generated for every time step interval as the scenario runs. To make the X-33 videos, SAIC set the time step interval to 0.034 seconds so that approximately 30 still frames were generated for every second of vehicle flight. Each frame is 640x480 and approximately 901 kilobytes in size. At 30 frames per second, and with about 13 minutes of flight time for the initial flight, about 20 gigabytes of still frame data results. The files were compressed and written to CDs for transporting data to build a video from the frames.

## **Pre-Planned Trajectory/Attitude**

Prior to the actual flights of the X-33 vehicle, visualizations are based on "pre-planned" trajectory and attitude data provided by the NASA MSFC Flight Mechanics, Guidance, Navigation, and Control Systems Branch. The data are the output of detailed six-degree-of-freedom calculations that are part of the X-33 design process within the government/industry collaboration between NASA and Lockheed Martin.

In using early design trajectories, smoothing was necessary for both trajectory and attitude information due to the different accuracy requirements for the simulation software and the relatively coarse preliminary design calculations. In later calculations obtained from NASA, however, the data were useable without modification, other than coordinate system changes.

The STK/VO software can operate by using any of a variety of inertial space and earth-fixed coordinate systems. In this application, oblate earth-fixed coordinates were used for the vehicle position. Depending on the input data source, either inertial space Euler angles or quaternions can be used to give the vehicle attitude. The result is a geographically-referenced spacecraft simulation based directly on data inputs from the designers. The same kind of methodology can be applied to a depiction of the vehicle state in real time by using the same simulation with down-linked trajectory data.

Pre-planned trajectories were provided for both the Haystack-to-Dugway and the Haystack-to-Malmstrom flights of the X-33 vehicle. In addition to visualization of the vehicle, terrain, and related scenery for the flights involved, the videos also include numerical representations of the trajectory parameters associated with the flight, including altitude, velocity, and downrange distance. Other vehicle features, such as sonic boom, exhaust plume, landing gear deployment, and flap position may also be included.

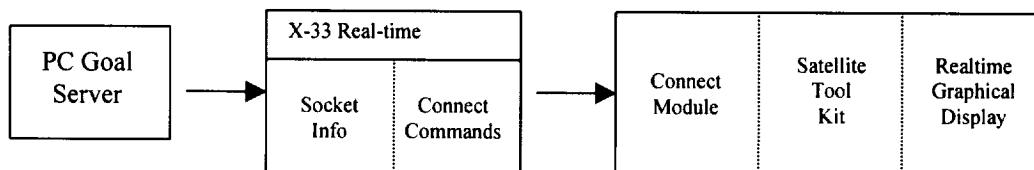
## Real-Time Trajectory/Attitude

*Real-time* visualization of a flight vehicle involves many links in the process of sending raw telemetry data from the vehicle across a network to a display on a computer workstation. If any of the links in the process is broken, the visualization will be impacted. The severity of the impact depends on the quantity of data lost due to the broken link. However, even when data are transferred smoothly, there is a certain inherent latency because of the time needed to travel from the data source to the computer display. This and other details of real-time X-33 visualization displays will be explained in greater detail in the following paragraphs. Near Real-Time Flight Visualization (NRT FV) is really a more accurate way to describe the visual display of the X-33 flight. Specifically, NRT refers to the latency inherent in the transmission of S-Band telemetry data from the X-33 vehicle to the ground station through the Database Server (DBS) PC-Goal Gateway (PCGS) to the PC-Goal User (PCGU). The data, which are transferred from the PCGS to the PCGU, are referred to as a User Datagram Protocol/Internet Protocol (UDP). The NRT FV capability (PCGU/consumer) uses a parsed version of the UDP data to generate a graphical display of the X-33 in flight. The real-time term is used to convey the idea that the data are used immediately upon arrival in the NRT FV software to present the X-33's attitude and position. **Figure 4** shows a simplified flow of how real-time telemetry data from an X-33 flight are passed from a data server to a computer display for real-time visualization.

Near Real-Time Flight Visualization provides the observer with visualization of the X-33 vehicle as it is in flight. The observer's position is from the vantage point of a "chase aircraft". Since no existing chase aircraft is capable of the X-33's Mach 10 velocity, the NRT FV capability is the only means by which a consistent vantage point for viewing X-33 in-flight characteristics is possible.

SAIC's role in the X-33 flight is to provide a means by which a real-time visualization of the X-33 may be viewed on a computer workstation monitor during flight and then broadcast as an analog signal for display on television, websites, and other public viewing sites. SAIC will provide a platform interface to the PCGS UDP data-stream comprised of an Intergraph TDZ2000, Folsom 9700XL Scan Converter, Windows NT 4.0 Operating System and the NRT FV software. The NRT FV software will be built using the Winsock 1.1 specification, Microsoft C++ 5.0, Microsoft Foundation Class (MFC), Analytical Graphics Incorporated's (AGI) Satellite Tool Kit (STK), and a Rocketdyne UDP packet specification. Lockheed Martin will provide required data to be used in parsing the UDP packet on their X-33 website. Parsing data consisting of a Test Configuration Identifier (TCID), a Master Measurement List (MML), and Measurement Identifier (MID) will be available from the Lockheed Martin X-33 website.

The NRT FV executable will consist of a program composed of three threads. An Executive Thread (ET), a synchronous network communication thread (CT), and visualization thread (VT). The ET is the main program. It provides the NTR FV framework. The CT collects data from the network and passes it on to the ET. The VT provides the user with a visualization of the X-33 in flight.



**FIGURE 4.** Process Data Flow of an X-33 Flight for Real Time Display

The Communication Thread (CT) creates and binds to a Window socket. The CT listens to the socket and collects PCGS datagrams. As datagrams arrive, the CT notifies the ET of their arrival. The CT takes advantage of synchronous blocking sockets and threads to provide a simplified communication interface. It communicates to the ET through event notification.

The ET, upon CT notification, reads a datagram and parses it to create time-tagged records describing position (altitude, longitude, latitude), velocity (north, east, down), attitude quaternion. The ET then transforms the data into VT compatible format and commands the VT.

During a build of the NRT software, libraries are "linked in" from an STK module called STK/Connect. These libraries allow an external application to send and receive data from STK. The VT uses the ET output and the functions of STK/Connect to read an external ephemeris file (position and attitude) and send these data back to STK where the visualization occurs. The VT is capable of interpolation and extrapolation of data between points such that the visualization occurs smoothly. The observer perceives that the X-33 is in flight. Using the 9700XL scan converter, the STK animation screen can be captured at every step and sent as an analog signal. This signal is then broadcast to television and the NASA X-33 website in near real-time. In this manner, the observer can watch a space vehicle in flight in a way that was never before possible.

## **Viewing Position Control**

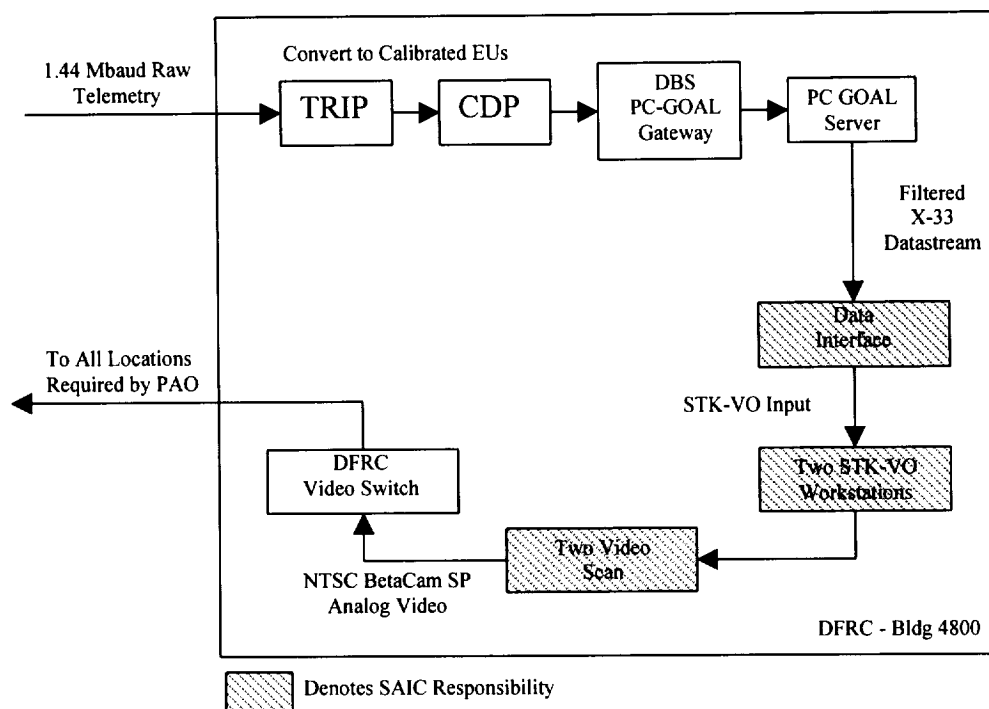
Joystick control of the observation vantage point was an early goal of SAIC's flight visualization activity. The motivation for this goal was to provide a capability tantamount to a "chase plane's" view of the X-33 vehicle over its entire flight trajectory. Early in the work it was noted that joystick-related variables were resident in the STK. A Microsoft SideWinder 3D Pro joystick was investigated for this application. It performed successfully in pitch and yaw control of the viewing position of the "chase plane". A Z-axis control was provided via joystick rotation to effect a "zoom" in/out capability. Further work is underway to provide capability for "multi-threading" to prevent loss of processor time while waiting for joystick input. Until this is resolved, the real-time STK scenario experiences a slight "jump" when the joystick is used to change the viewpoint.

Panoramic viewing of the X-33 vehicle and its background terrain was also provided by rotating the view direction in the X-33 scenario and taking "snapshots" from the STK program. These were then assembled into a 360 degree digital panoramic image and the seams between separate snapshots were eliminated. On the website, the user will be able to use the computer's mouse to orient the viewpoint and scan around the X-33 and background scenes.

## **Telemetry and Visualization Interfaces**

As mentioned above, the flight data required to provide accurate visualization of the X-33 flight test include altitude, attitude (in quaternions), acceleration, time stamp, control surface movements, landing gear deployment, and engine burn indication. The block diagram in **Figure 5** depicts the interface of the visualization hardware at the Dryden Flight Research Center.

The 1.44 Mb/sec downlink telemetry is pre-processed and distributed to the downstream users in PC-GOAL format. The data stream will be filtered to provide the STK/VO workstations with individual parameters defined by the aforementioned requirements. These X-33 data must be provided to the visualization at as high a data rate as possible to support the 30 frames-per-second video output rate. The workstation will be equipped with interface software to accommodate the incoming data and a video scan converter to transform the monitor signal into the required NTSC BetaCam SP video output. The video output is connected to a DFRC video switch that forwards the video as required.



**FIGURE 5.** Visualization Hardware Interfaces

## CONCLUSIONS

The X-33 flight visualization effort has resulted in the integration of high-resolution terrain data with vehicle position and attitude data for planned flights of the X-33 vehicle from its launch site at Edwards AFB, California, to landings at Michael Army Air Field, Utah, and Maelstrom AFB, Montana. Video and Web Site representations of these flight visualizations were produced. In addition, a totally new module was developed to control viewpoints in real-time using a joystick input. Efforts have been initiated, and are presently being continued, for real-time flight coverage visualizations using the data streams from the X-33 vehicle flights. The flight visualizations that have resulted thus far give convincing support to the expectation that the flights of the X-33 will be exciting and significant space flight milestones... flights of this nation's one-half scale predecessor to its first single-stage-to-orbit, fully-reusable launch vehicle system.

## ACKNOWLEDGEMENTS

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